University of California
Lawrence Livermore
National Laboratory

LLNL File No. IL10507

RE

ATTACHMENT A

This invention was made in the course of or under prime Contract No. W-74[illegible]ENG-48 between the U.S. Department of Energy and the University of California. This Record of Invention is prepared for the Office of [illegible]sistant General Counsel for Patents, U.S. Department of Energy.

LLNL PATENT GROUP

I. Title of the Invention

Optical coatings for parasitic suppression with near unity low angle reflectivity

II. Inventor Information

LLNL Inventor(s) (First, Middle, Last)	Title/Position	Directorate	Payroll Acct	Phone Number	Mail Stop
Eric C. Honea	Physicist	Lasers	9873-00	2-8118	L-441
Raymond J. Beach	Physicist	Lasers	9873-00	3-8986	L-441

Non-LLNL Inventor(s) (F, M, L)	Title/Position	Employer	Phone Number	Fax Number	Subcontract #

III. Abstract

Using transparent optical coatings of controlled index, we have demonstrated a laser gain element with total-internal-reflection used to confine pump light while suppressing parasitic oscillations which would otherwise deplete the stored energy. The index of refraction of the transparent optical coating determines which rays undergo reflection at the interface between the gain element material and optical coating. Rays with angles larger than this critical angle for total internal reflection reach the outer surface of the coating. By depositing a diffuse reflectance material such as powdered $BaSO_4$, an absorbing film such as Ge, or roughening the surface to reduce the specular reflectivity, these rays can be absorbed or scattered. The principle was demonstrated with a rectangular parallelpiped Yb:YAG slab of dimensions 2.5 x 3.5 x 100 mm using Al_2O_3 coatings and a combination of India ink and $BaSO_4$ diffuse reflectance material on the outer surfaces. The experiments showed a net gain of 0.8 nepers compared to a predicted value of 0 nepers without the coatings.

IV. Keywords for Potential Licensees

List keywords for database searches for appropriate companies to contact concerning your invention.

Parasitic laser oscillations, diode-pumped solid-state lasers

V. Keywords for Patent Search

List keywords we can use for an effective patent search.

Parasitic laser oscillations, diode-pumped solid-state lasers

Proprietary Information

LL6419# v2.1 (7/98)

University of California
Lawrence Livermore National Laboratory

RECORD OF INVENTION

LLNL File No.

VI. Uses of the Invention

List past uses, current uses and potential uses for your invention

LLNL r Government uses or possibilities for use:

Parasitic suppression in solid-state laser devices where the laser or pump beams are reflected off of a surface of the gain element. For applications involving laser illumination, materials processing and laser weapons.

Commercial or other uses or possibilities for use:

Same as above.

VII. Documents Describing the Invention

Documents, publications, and presentations describing the invention that you have published or prepared for publication, or presented on the subject. Also include presentations and publications planned within one year from now. Please attach a copy of preprints, articles, or viewgraphs.

Title/Subject	Date	Publication #
Briefing to Boeing (formerly Rockwell): "Kilowatt-class Yb:YAG slab laser for illuminator applications"		
Air Force personnel from Phillips Lab		
Briefing to CRADA partner personnel		

VIII. Documents Describing Prior Art (Please include copies of these documents.)

Related Documents (including patents, other publications) Please include patent numbers, authors, title, publication date, etc.

"Parasitic Oscillation Suppression in Solid State Lasers using Absorbing Thin Films", Patent No. 5,335,237 Luis Zapata, and references therein.

LLNL File No.

IX. Background

Background of the invention, including technical problems addressed by it

In many laser devices the laser and/or pump beams are reflected off of a polished face of the laser gain element. For instance, the zig-zag slab laser geometry relies on low-loss reflections of the laser beam, and many systems confine diode pump light by total internal reflection off of polished faces of the laser rod or slab. Since parasitic oscillations or amplified spontaneous emission can also reflect off of these faces, it is usually necessary to take great care to avoid geometries where rays can be reflected with low loss and path lengths long enough to result in substantial amplification and depletion of the stored energy. In cases where these undesirable rays fill the entire gain volume, the entire stored energy can be depleted befor useful extraction. In particular, some of these undesirable rays can be trapped in the laser volume via total-internal reflections, suffering little or no loss. This can prevent any useful gain > 0 nepers.

Lasers to date have solved this problem by applying a ground finish to reduce the specular reflectivity, or applying an absorbing film or layer to some of the surfaces of the laser gain element. This limits the design options since the limited reflectivity can impact pump delivery or possible laser geometries. Our invention enables surfaces to have low specular reflectivity for high angles which would be sampled by parasitic oscillations, but maintain high reflectivity for low angles useful for confining pump light or reflecting the laser beam.

X Invention Description

Description of the invention (you may also attach a paper). Please include a sketch of the invention, if possible.

Figure 1 (attached) shows a surface of a laser gain element with incident rays r1 and r2 at angles θ1 and θ2. The surface of the gain element (with index n1) shown in the figure has a transparent coating of index n2. For coating thicknesses sufficiently large, angles θ1>ArcSin(n2/n1) are reflected at the gain element/coating interface by total internal reflection. Alternately, rays of angle θ2<ArcSin(n2/n1) are transmitted into the coating. In our invention this second surface of the coating has a low specular reflectivity which prevents the ray from being reflected back into the laser gain element, even if the index if the surrounding medium is such that the ray might otherwise be reflected by total internal reflection. (If the reflection from this other surface is not suppressed, note that rays could still undergo total internal reflection for θ3>ArcSin(n2/n3) where n3 is the index of the surrounding medium, i.e. coolant). This low specular reflectivity can be obtained by depositing an absorbing medium on top of the coating of index n2, or introducing a surface or medium which scatters incident light. The latter can be obtained by roughening the surface or applying a diffusely scattering material such as particles of $BaSO_4$.

The utility of this invention has been demonstrated by ray-trace calculations and experiments on a rectangular parallelpiped Yb:YAG slab laser gain element. For a rectangular parallelpiped slab surrounded on four sides by a medium of index n3, and index n1 (air) on the remaining two end faces, it can be shown that parasitic rays can be completely trapped by total internal reflection (i.e. with zero loss) if n3<(n1^2-1/2)^1/2 (see attached Figures 2 and 3). For $Y_3Al_5O_{12}$ of index n1=1.82, this critical index for the surrounding medium is n3=1.677. Since common coolants such as water (n3=1.33) have an index much lower, rectangular parallelpiped slabs with polished faces on all six sides are avoided because of the presence of nearly zero loss parasitics which sweep out any stored energy. Note that if we only had to worry about rays in two dimensions, we would simply require that the critical angle for total internal reflection be greater than 45 degrees, i.e. 45<ArcSin(n1/n3). In this way, a ray that was incident at angles θ and 90-θ at the two perpindicular faces and would not undergo total internal reflection at both faces.

For our experimental demonstration, we used a Yb:YAG rectangular parallelpiped slab gain element 2.5 x 3.5 x 100 mm, with coatings on the 2.5 x 100 and 3.5 x 100 mm sides to suppress parasitics. The 2.5 x 3.5 mm end faces had antireflection coatings for normal incidence 941 nm pump and 1030 nm amplified light. (continued)

LLNL File No.

X. Invention Description (continued)

Description of the invention (you may also attach a paper). Please include a sketch of the invention, if possible.

We wanted to maintain high reflectivity for shallow angles such that the pump light at 941 nm and the laser light at 1030 nm would undergo total internal reflection with zero loss. Therefore, we wanted to apply a coating of index only slightly larger than the n=1.677 value in order to maintain reflectivity over the widest range of angles without trapping parasitic rays. Since no standard thin film materials are very near this index, we initially used Al2O3 coatings (n=1.62) despite its index being slightly below the desired value and then for our second iteration we used a multilayer of Al2O3 and HfO2 to yield an effective index of n=1.7. The latter was calculated using a commercially available multilayer thin film computer program (TFCalc).

To suppress the reflectivity of the outer surfaces of the coating, we identified several possible methods. A straightforward method is to apply an absorbing film such as Ge or Cr, although this would result in local heating as fluorescence and ASE is absorbed in the thin coating. Alternately, a diffusely reflecting surface can be obtained by applying a thick layer of nonabsorbing particles of sizes on the order of the wavelength of the incident light. This is the basis for the BaSO4 coatings commercially sold by Kodak for diffuse reflectors (e.g. integrating spheres). We also investigated Al2O3 and ZrO2 "high temperature paint" which was found to survive >100 W/cm^2 1.064 µm light. Since the BaSO4 was straightforward to apply most of our experiments used this material. We also investigated the possibility of obtaining a ground surface finish on the exterior of the parasitic suppression coating. One option investigated here was to use ZnS as a soft, layer to be ground, with the harder oxide material as the etch stop. This seemed to be a higher risk approach and was shelved until deemed necessary.

In a zig-zag slab, only two of the faces are cooled in order to maintain one-dimensional heat flow. On these faces we decided that absorbing the fluorescence would be the best solution since this could be done with very high efficiency. In this case, the cooled side faces (3.5 x 100 mm) had the n=1.7 multilayer cladded by an absorbing layer of Ge. The top and bottom faces (2.5 x 100 mm) of the slab, which are usually insulated in the zig-zag design, had the n=1.7 coating with BaSO4 particles applied to the outer surface. The attached Figure 4 shows the calculated reflectivity vs angle at 1030 nm for the 3.5 x 100 mm faces. Using a He-Ne probe beam, we verified the sharp angular cutoff at the internal angle of ~70 degrees.

Figure 5 shows the utility of these coatings verified with pulsed gain measurements performed on the Yb:YAG slab. With the coatings, a gain of 0.8 nepers was achieved in a geometry that would otherwise not generate any gain (i.e. 0 nepers)

This approach can also be applied to other laser gain element geometries such as rods. Measurements of the gain profile in our rods with polished barrels indicate the presence of barrel modes trapped in a radius r > r(rod)*n(coolant)/n(YAG). The attached viewgraphs describe an approach which was proposed but not implemented for reducing the effects of the trapped barrel modes.

XI. Inventor Information

Inventor's Permanent Home Address (Please attach a separate sheet for additional inventors.)

Full Name	Citizenship	Street Address	City, State, Zip Code
Eric C. Honea	US	12034 Glenora Way	Sunol, CA 94586
Raymond J. Beach	US	1599 Cross Creek Place	Livermore, CA 94550

LLNL File No.

XII. Funding Source

Funding Source or Project Under Which the Invention Arose (Include subcontracts, CRADAs, international agreements, work for others, or special project information.)

Boeing (Formerly Rockwell) CRADA TC0195-92

Resource Manager: Kathy Allen	Phone #: 3-4009	Is funding presently being provided for development of your invention? ☐ Yes ■ No
LLNL Acct #: 4720-35	B&R #: DP0301C1C	Please state the source of funds (if same as above, please so state)
Subcontract #	DOE Program Code	Do you reasonably expect future funding from the current source or other sources? ☐ Yes ☐ No
CRADA #	Work for Others #	If yes, what is that source?

XIII. Conception of the Invention

Conception Date:	Conception Place: LLNL

Earliest documentation of your invention (please provide date and identify the document)

Thermal calculations for slab laser incorporating these coatings were performed May 1997. Test coatings on YAG witness samples ordered 6/23/97 from Quality Thin Films (Oldsmar, Florida)

First Sketch or Drawing Date:

First Written Description Date:

Names of Witnesses or others with knowledge of facts relating to conception (preferably at least 2)

Full Name	Organization	Telephone Number
William F. Krupke	LLNL	(925) 422-5905
Steven A. Payne	LLNL	(925) 423-0570

XIV. Reduction To Practice of the Invention

Date first model completed:	Date of operation and testing:	Place of test: LLNL, B166

Results of testing

First tests showed parasitic threshold of 0.35 nepers of gain, improved design (Dec 1997) showed 0.8 nepers

Witnesses or others with direct knowledge of test (preferably at least 2)

Full Name	Organization	Telephone Number
Joel Speth	Lasers	(925) 422-2291
Scott Mitchell	Lasers	(925) 423-8843

XV. Invention Use and Disclosure

Has the invention been put into use? ■ Yes ☐ No

Is the invention scheduled to be put into use? ■ Yes ☐ No

If yes, explain

Has the invention been disclosed to non-LLNL personnel? ■ Yes ☐ No

If yes, was the disclosure done under a non-disclosure agreement? ☐ Yes ☐ No

If yes, to whom and when?

Name	Date
Dennis Harris, Boeing (Formerly Rockwell)	
Petras Avizonis, Boeing (Formerly Rockwell)	

LLNL File No.

XVI. I/We believe myself/ourselves to be the first and original inventor(s) of the above-described invention.

Inventor Signature	Date	Witness Signature	Date
[illegible]		Christine Peaslee	
Raymond J. Beach		Christine Peaslee	

XVII. Classification Review

Basis for unclassified release:

- ☐ Outside scope of AEA and EO
- ☐ CG-DAR-1, Topic(s) ________
- ☐ Other Guide(s) ________

Topic(s) ________

UCNI ☐ Yes ☐ No   If YES, Guide ________

See next page

Authorized Derivative Classifier	Name and Title	Signature
Confirming Reviewer	Name and Title	Signature

XVIII. For LLNL Patent Group Use Only

Possible Statutory Bars	Publication	
	Public Use/Sale	
Recommended Filing Date Due to Possible Statutory Bars		
Preliminary Review by:	Date	

Send the completed and signed form to the Patent Group at L-703

LLNL File No.

XVI. I/We believe myself/ourselves to be the first and original inventor(s) of the above-described invention.

Inventor Signature	Date	Witness Signature	Date
Eric C Hu		Kristie Pegalee	
Raymond J. Beach		Christine Peaslee	

XVII. Classification Review

Basis for unclassified release:

- [x] Outside scope of AEA and EO
- [ ] CG-DAR-1, Topic(s) ____
- [ ] Other Guide(s) ____

Topic(s) ____

UCNI ☐ Yes ☐ No   If YES, Guide ____

	Name and Title	Signature
Authorized Derivative Classifier	Joseph R Milhe Business Development Specialist	Joseph R Milhe
Confirming Reviewer	Wm. A. Bollinger Classification Advisor	Wm. A. Bollinger

XVIII. For LLNL Patent Group Use Only

Possible Statutory Bars	Publication	
	Public Use/Sale	

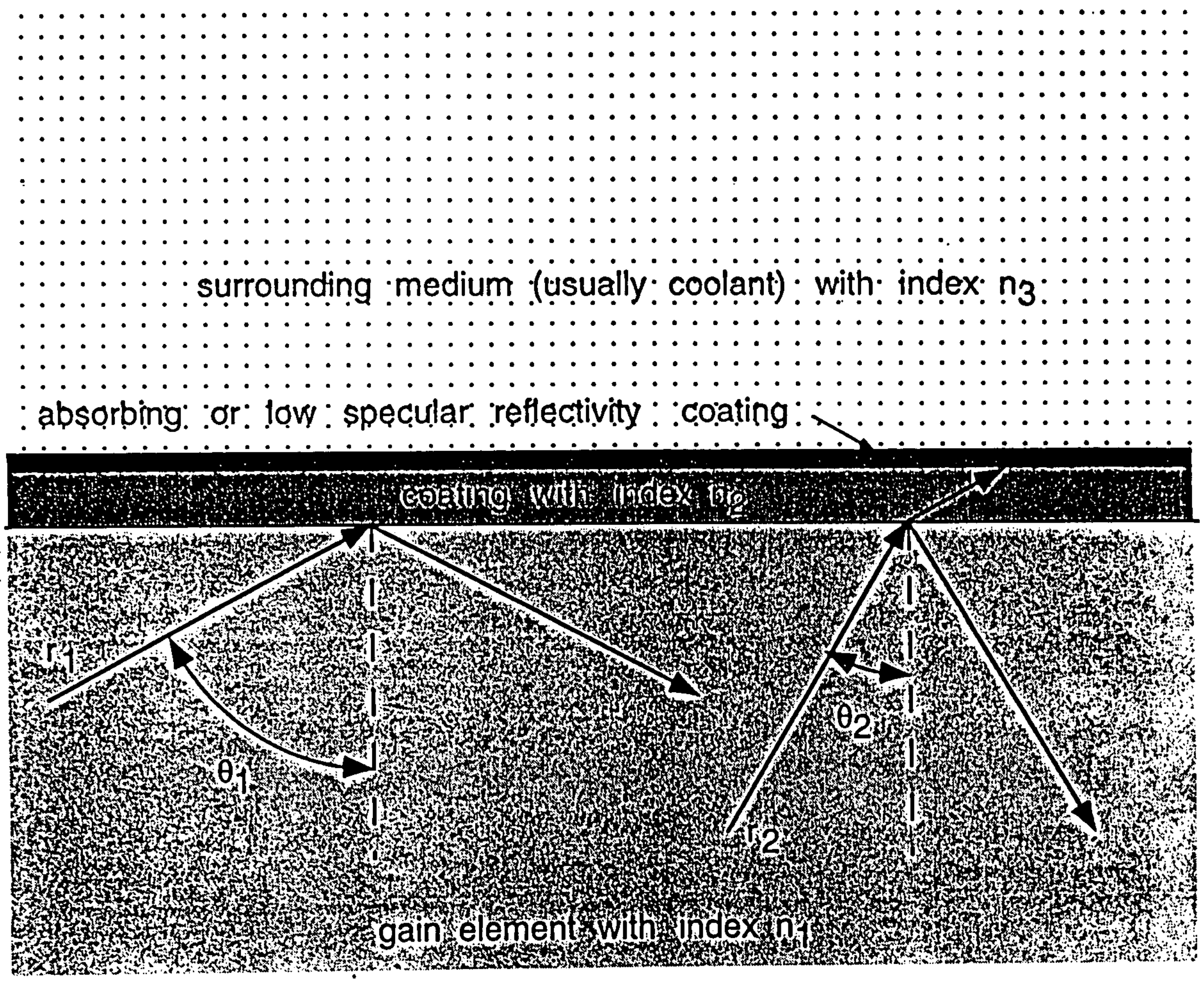
Recommended Filing Date Due to Possible Statutory Bars

Preliminary Review by:	Date

Send the completed and signed form to the Patent Group at L-703

Proprietary Information

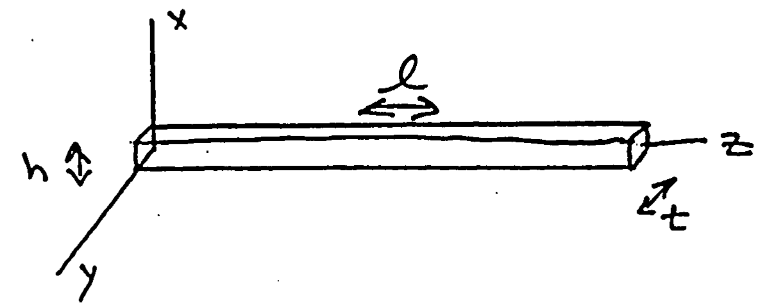
Figure 1.

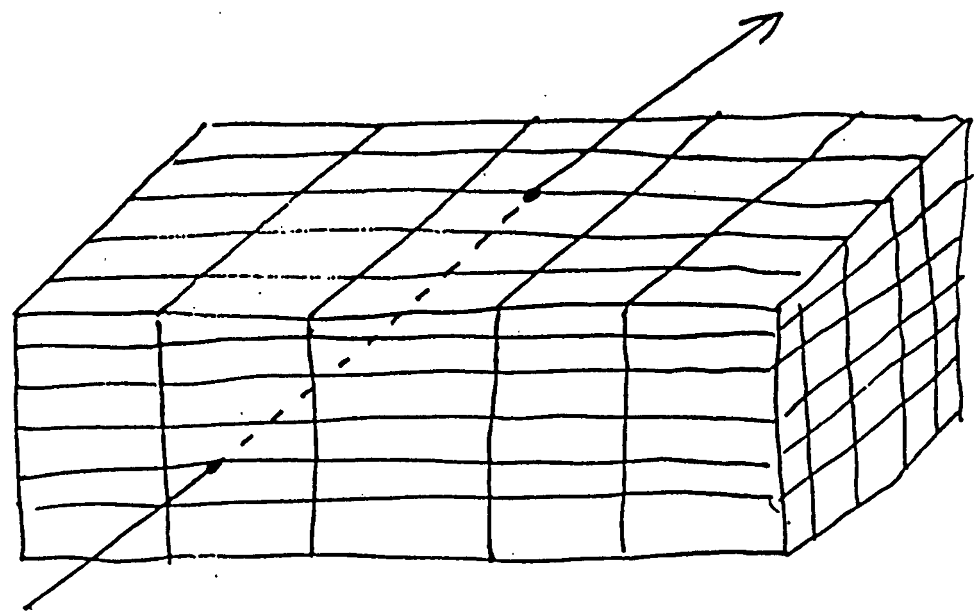


surrounding medium (usually coolant) with index n3
absorbing or low specular reflectivity coating
coating with index n2
r1
θ1
r2
θ2
gain element with index n1

Parasitic propagation directions can be identified using a method of images construction

Fig 2





fill space using slab and slab images

- Define arbitrary ray direction using direction cosines $(\cos\theta_x, \cos\theta_y, \cos\theta_z)$
- Gain of ray is given in nepers/cm by

$$g = \cancel{\ln}\ \frac{\ln(\mathrm{Ref}x)}{(h/\cos\theta_x)} \quad \frac{\ln(\mathrm{Ref}y)}{(t/\cos\theta_y)} \quad \frac{\ln(\mathrm{Ref}z)}{(l/\cos\theta_z)} \quad \alpha$$

where: Ref i is the reflection coefficient for i-oriented plane
α is slab specific gain loading

zero- loss parasitics correspond to those ray directions that are confined by TIR at all three sets of planes

Fig 3

TIR condition

$$\begin{cases} \cos\theta_x < \cos\theta_{x\text{-crit}} = \dfrac{\sqrt{n_s^2 - n_c^2}}{n_s} \\ \cos\theta_y < \cos\theta_{y\text{-crit}} = \dfrac{\sqrt{n_s^2 - n_c^2}}{n_s} \\ \cos\theta_z < \cos\theta_{z\text{-crit}} = \dfrac{\sqrt{n_s^2 - 1}}{n_s} \end{cases}$$

where:
n_s = slab i[illegible]
n_c = c[illegible]atin[illegible]
i[illegible]

- since $1 = \cos\theta_x^2 + \cos\theta_y^2 + \cos\theta_z^2$, zero loss parasitics exist when

$$1 < \frac{n_s^2 - n_c^2}{n_s^2} + \frac{n_s^2 - n_c^2}{n_s^2} + \frac{n_s^2 - 1}{n_s^2}$$

or

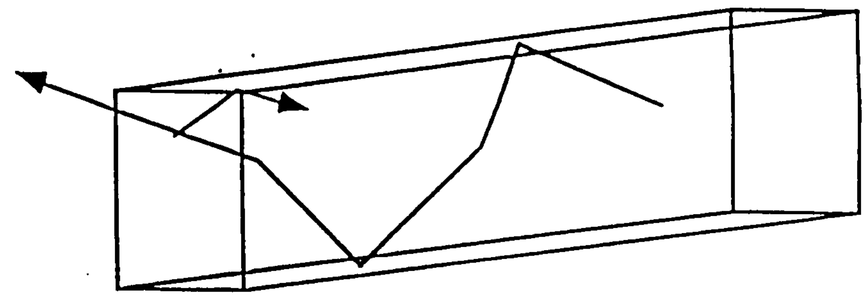
$$n_c < \sqrt{n_s^2 - 1/2}$$

zero-loss parasitics can be completely suppressed by choosing a cladding with refractive index large enough

$$n_c > \sqrt{n_s^2 - \frac{1}{2}}$$

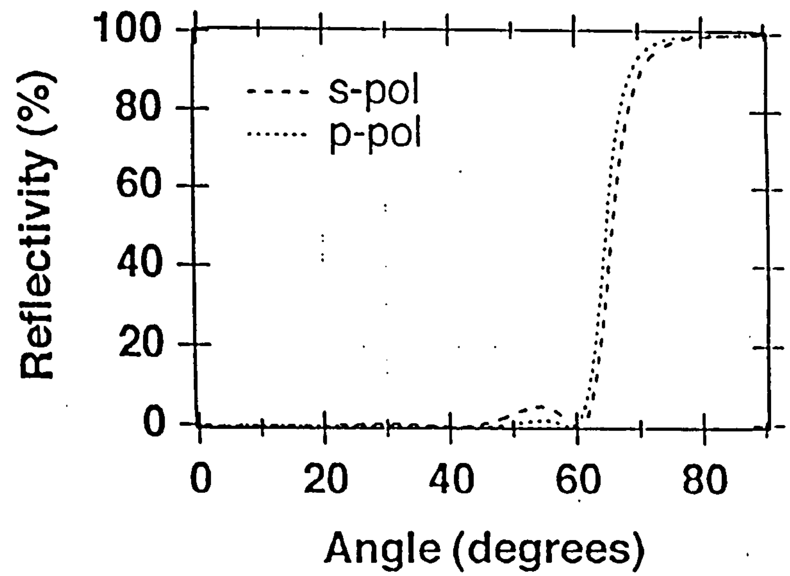
Figure 4.

We have demonstrated parasitic suppression using a novel dielectric coating and surface conditioning method



Detailed analysis of rays in a rectangular YAG slab shows that low threshold parasitics require bounce angles < 67 degrees on the four long faces

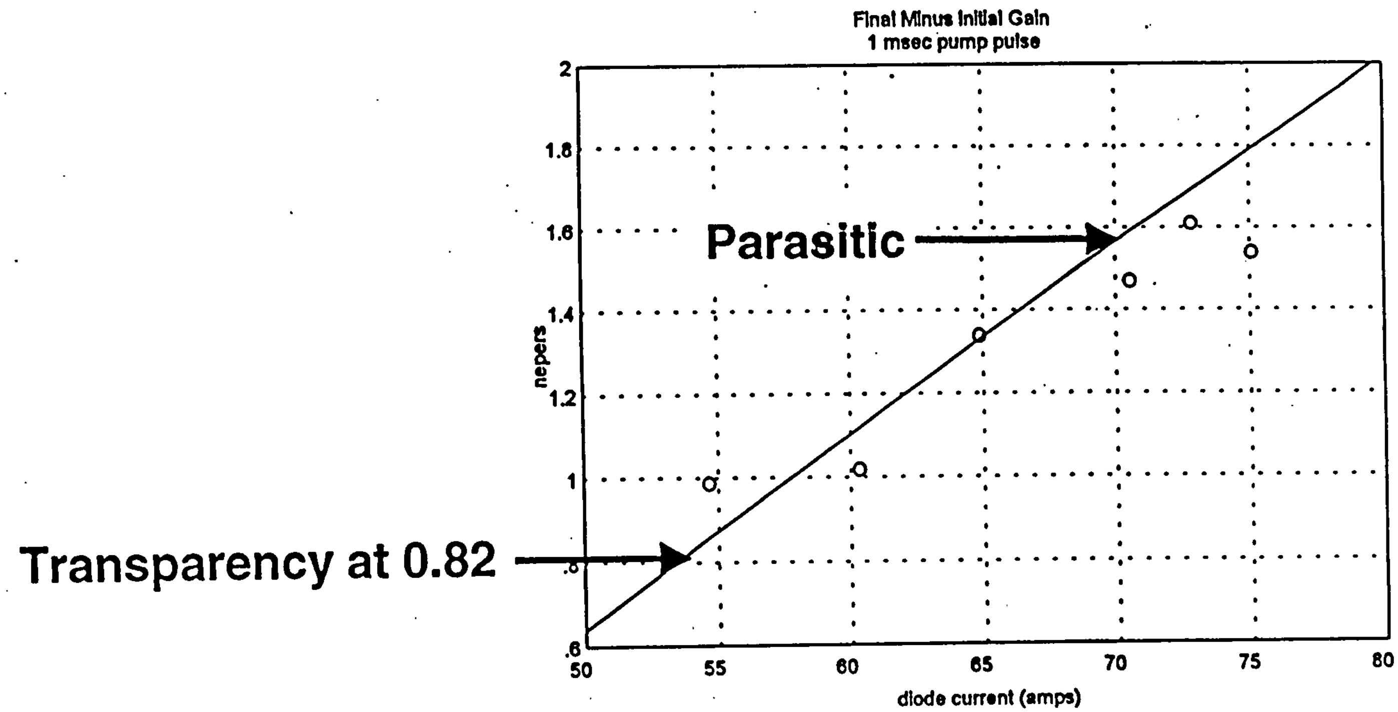
- We have designed dielectric coatings for the four long faces which provide high reflectivity for the shallow angle zig-zag laser beam and diode pump rays while suppressing higher angle parasitic rays



Measured gain of up to 0.8 nepers demonstrates successful suppression of parastics as required for our MOPA design

Fig 5

At absolute gains of 0.8 nepers (0.8 nepers above transparency) we see the onset of a hard, gain-clamping, parasitic mode



- Specified full power operating point of the laser requires an absolute gain of ~0.70 nepers above transparency
- Slab is conditioned with Al_2O_3 coating, as well as Barium Sulfate on its top and bottom surfaces and black ink over the central 3 cm of its side surfaces

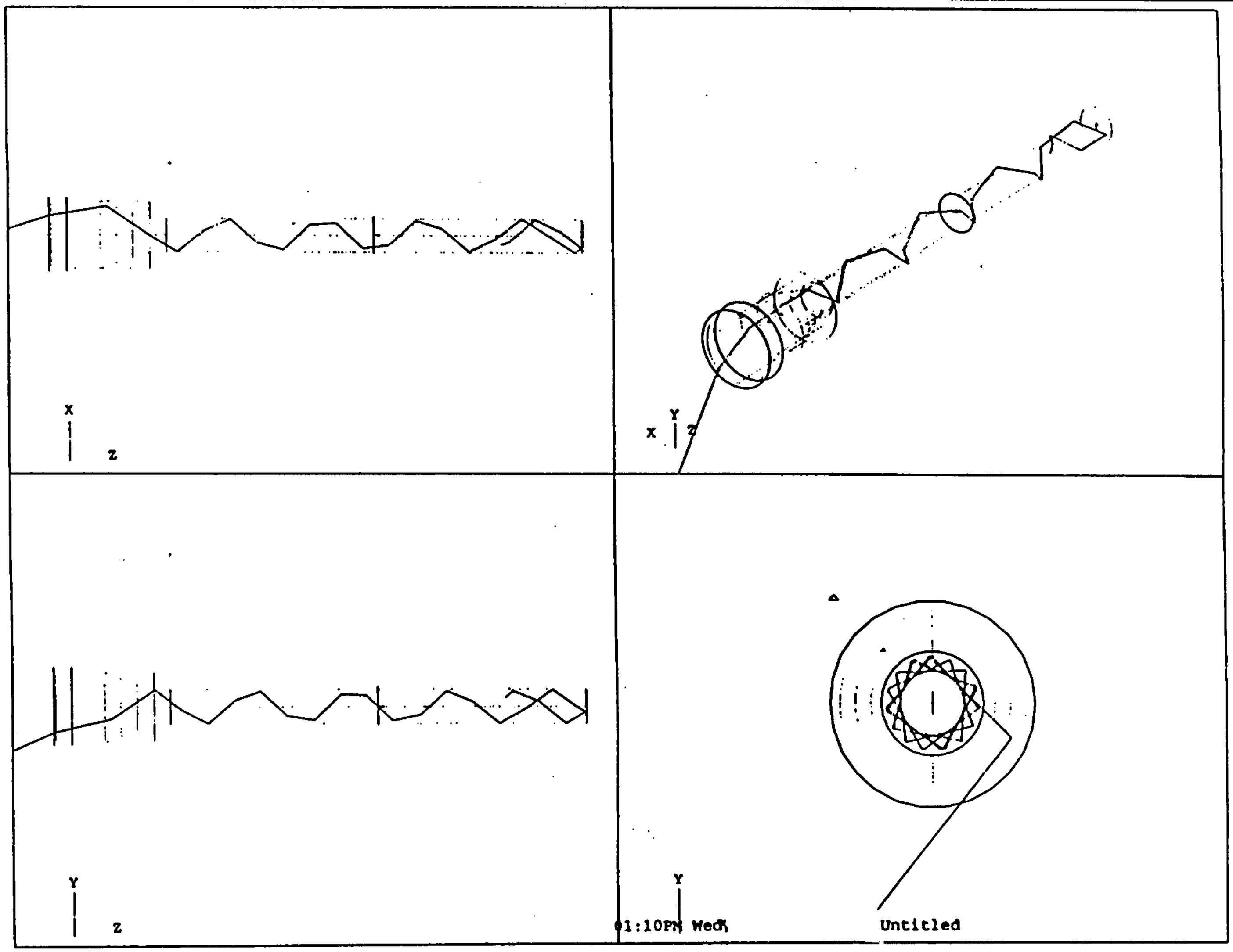
Parasitic Suppression Coatings proposed for rod laser gain element

400 W Yb:YAG Birefringence-Compensated Power Oscillator (BCPO) Illuminator

Technical Interchange Meeting

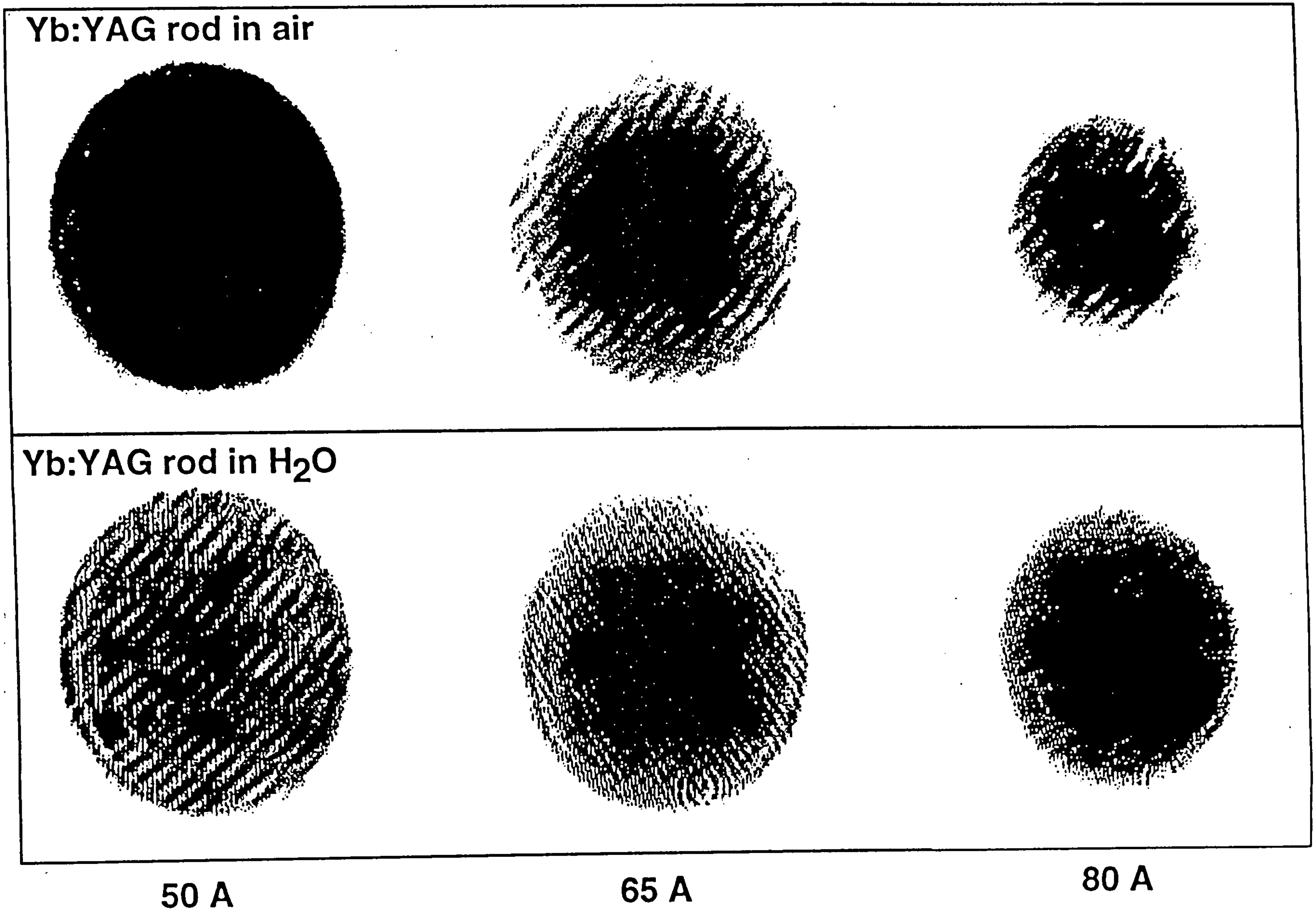
Eric Honea and Ray Beach
Advanced Lasers and Components

Although the flanged end caps are effective in outcoupling the ASE trapped in barrel modes, the path lengths can still be very long



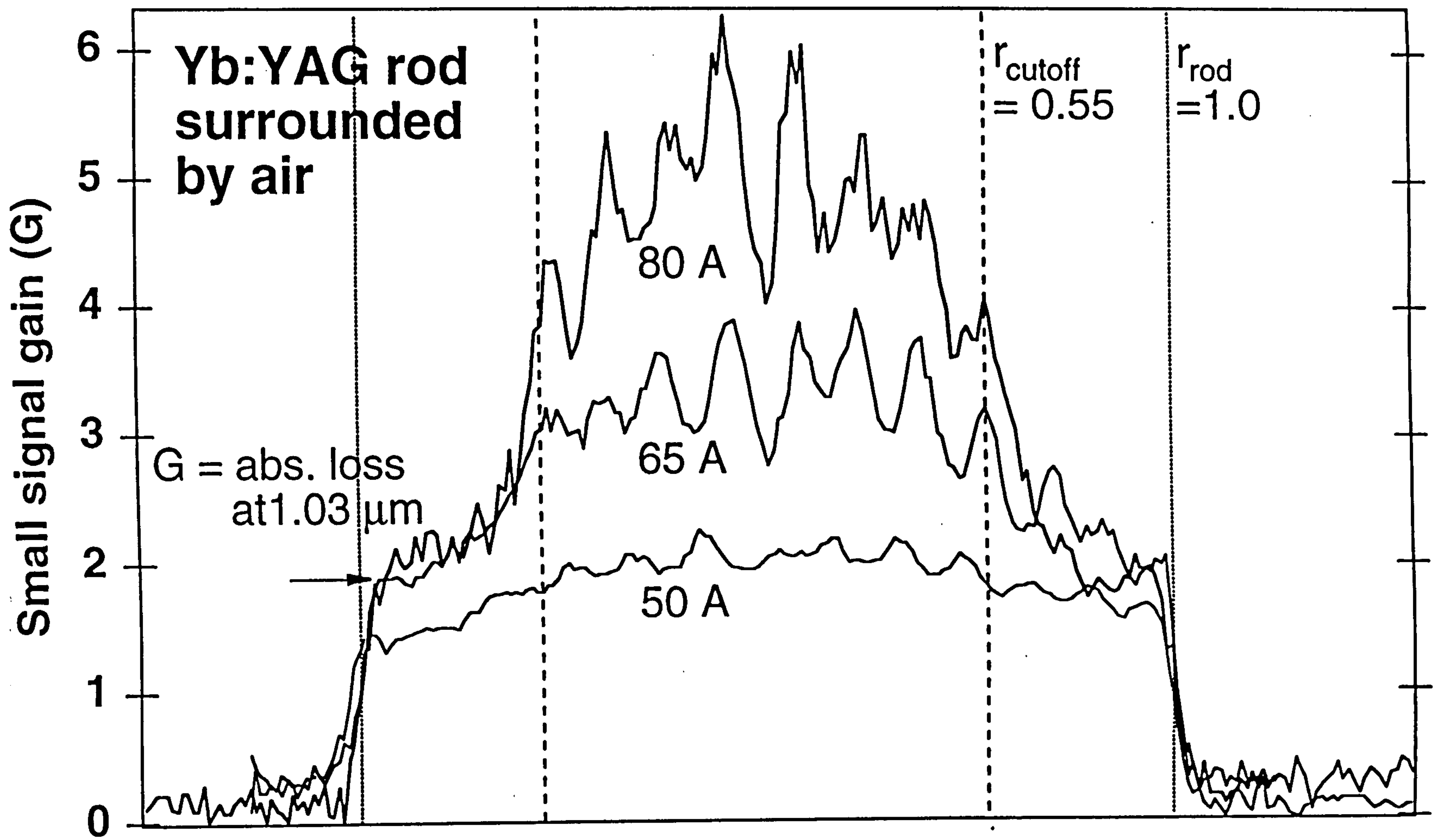
The longest path length barrel modes have $k_z \sim 0$ and are trapped within a region $r > r_c$ where $r_c = r_{rod} * n_{coolant}/n_{rod}$

Spatially resolved gain measurements clearly show depletion due to ASE confined in barrel modes



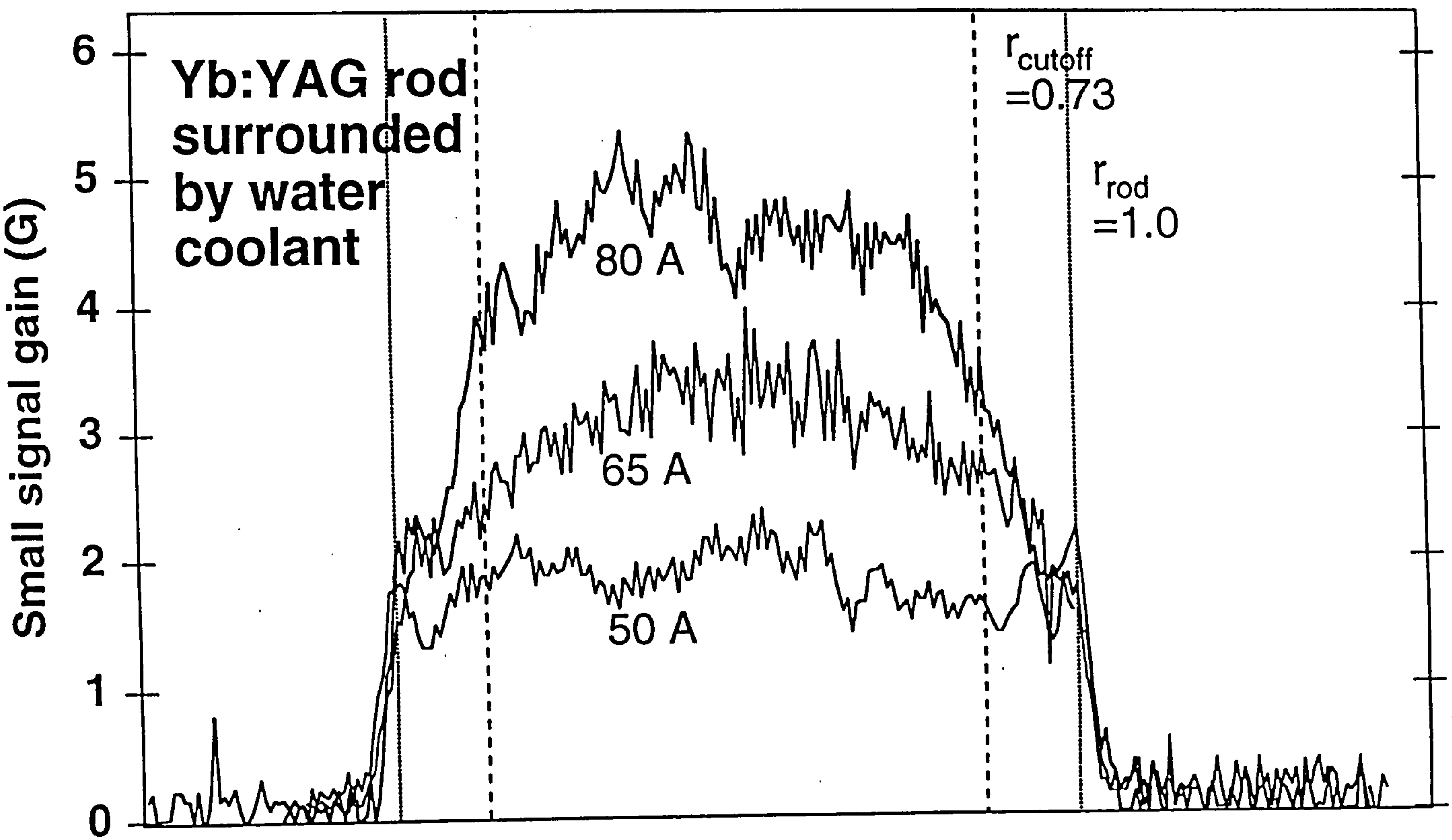
EHonea

Lineouts of spatially resolved gain profiles show clear evidence of gain clamping for $r > r_{cutoff}$ where $r_{cutoff} = r_{rod} * n_{coolant} / n_{YAG}$



EHonea

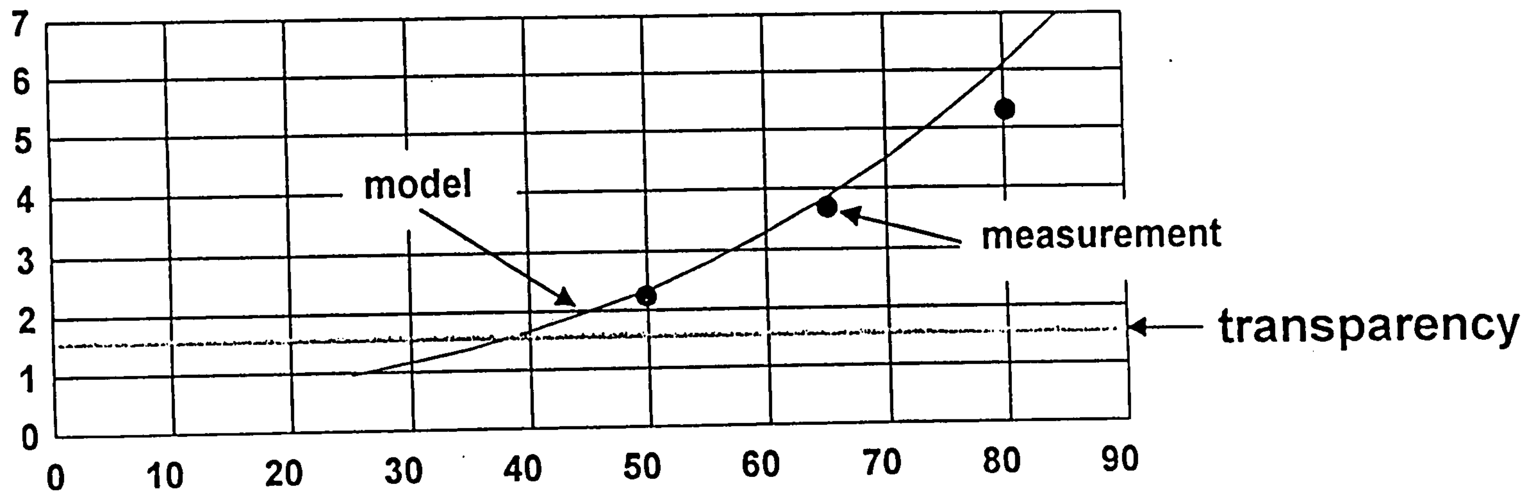
With water or other high index coolants surrounding the rod, the useful cross-sectional area of the rod is increased



We have measured and modeled the on axis gain (spatially resolved) in the laser rod

Our measurements confirm that the on axis gain is not sensitive to the material surrounding the rod barrel (e.g. air or water)

Small Signal Gain (G)
(900 usec pump pulse)



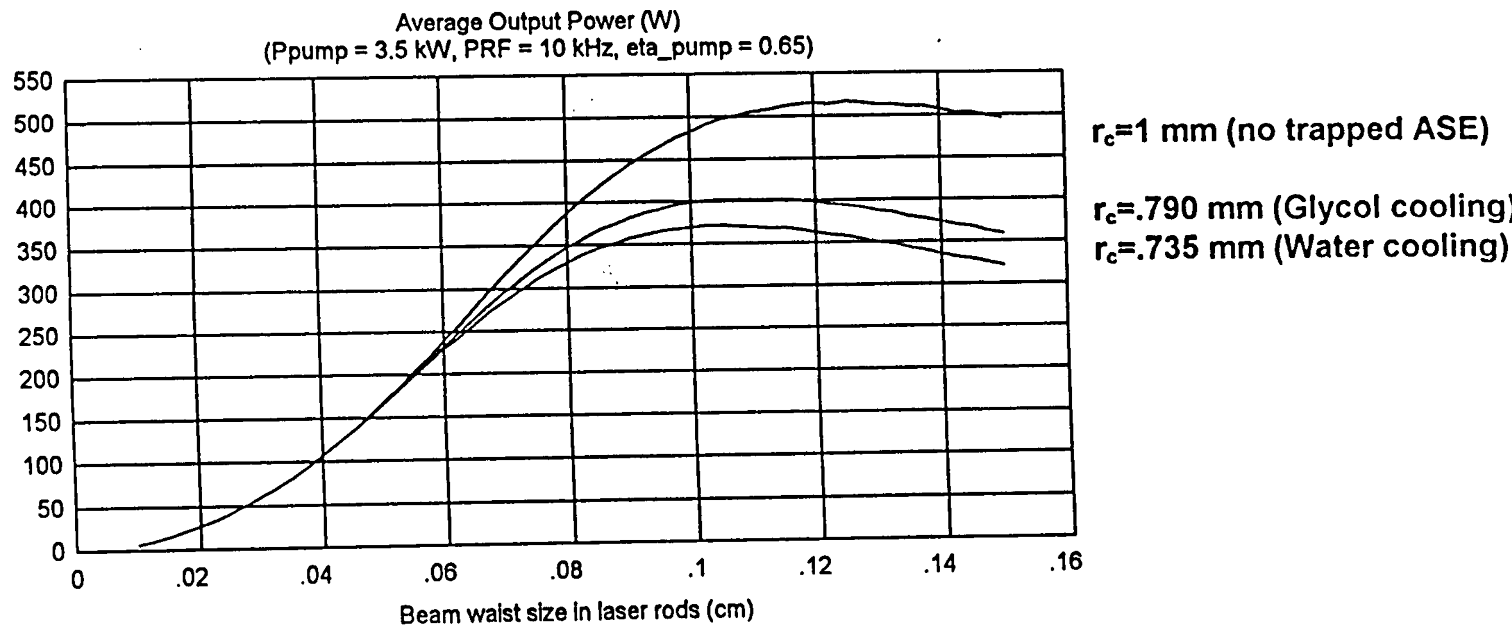
diode current (amps)

The deviation from the model may be due to untrapped ASE and possibly thermal effects such as the diodes tuning off the peak of the absorption

We have modified our laser codes to account for trapped ASE depleting the gain around the perimeter of the laser rod

- The gain loaded mode volume is now limited by a cutoff radius, r_c (for $r>r_c$, $g=0$)

$$modefill = \frac{1}{2}\left(\frac{\omega_0}{r_0}\right)^2\left(1-e^{-2(r_c/\omega_0)^2}\right)$$



If we can devise a method to eliminate or reduce trapped ASE, then for a 1 mm beam waist we can increase the average output power of the system from ~390 W to 480 W

A small improvement in gain area can be obtained with a higher index coolant such as ethylene glycol, but we have also identified two approaches to significantly improve the available gain

Since the mode propagating in the rod is a gaussian, the impact on laser performance is a convolution of the gain profile and the gaussian mode (which is a function of resonator parameters).

If the coolant can be changed from water to a higher index fluid such as ethylene glycol (n=1.43 compared to n=1.33) without impacting heat transfer, the available area can be increased to 62% from 53%.

- One approach to significantly improve the available gain area is to use a cladding layer of controlled index with an outer layer to absorb or diffusely scatter the ASE

    -We estimate the available area can be increased to 85%

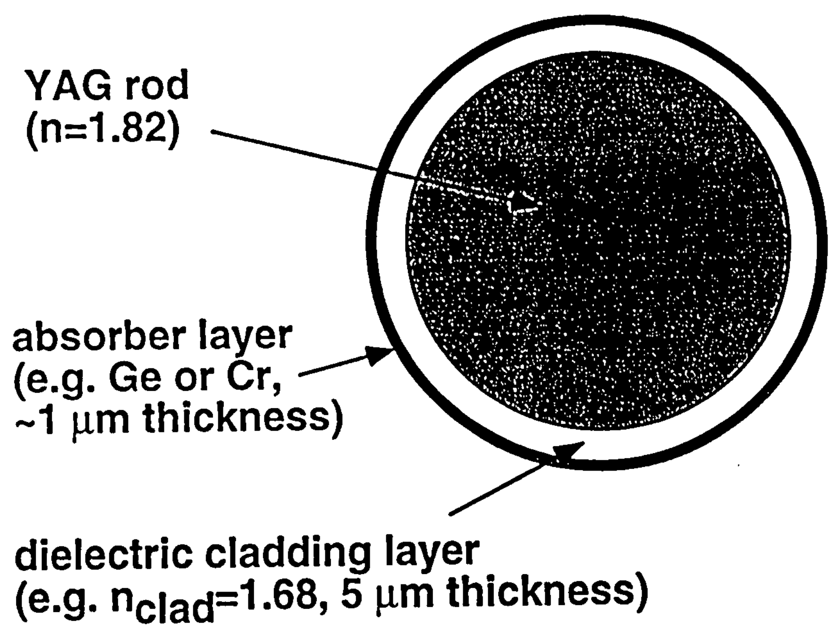
A second approach relies on the use of tapered rods to add a k_z component with each reflection, thereby preventing the path length from becoming infinitely long for rays with k_z initially ~ 0

-Relatively small tapers can decrease the path length from infinity to a few tens of cm (Ray Beach calculation)

Similar to theYb:YAG slab scheme for parasitic suppression, we can reduce the rod area depleted by ASE using appropriately designed coatings

By applying a coating of a given index to the outside of the rod barrel, we can control which rays will undergo total internal reflection (TIR) at the rod/coating interface

Rays with an incidence angle greater than the TIR angle go through the coating to reach a second absorbing or scattering coating



-since the pump light is confined by TIR, we need to choose n_{clad} to outcouple as much ASE as possible without frustrating the pump

-a preliminary estimate is that the available area for gain can be increased to 85% of the rod area, from the present 53% value